Measurements of W Boson Mass and Width

- Electroweak constraints on the Standard Model
- New W mass from CDF
- Predictions for the Higgs
- Measurements of the W width from the Tevatron
- Future prospects

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The Electroweak Standard Model

- The Higgs mechanism provides an elegant prediction for the W mass

Measured to 0.015%

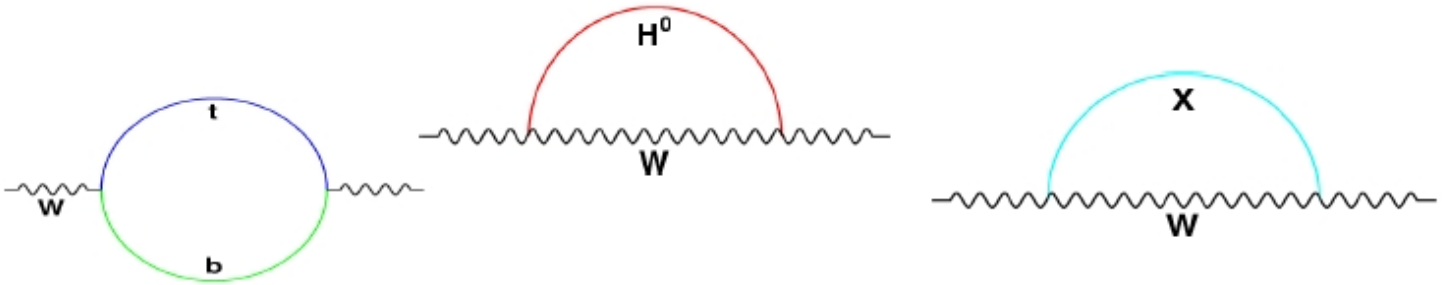
Measured to 0.002%

Measured to 0.036%

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F} \frac{1}{(1-(M_W^2/M_Z^2))} \frac{1}{(1-\Delta r)}$$

Measured to 0.0009%

Δr: O(3%) radiative corrections dominated by *tb* and Higgs



- With ultimate precision can set limits on other new particles, X, in loops

Radiative Corrections to the W Mass

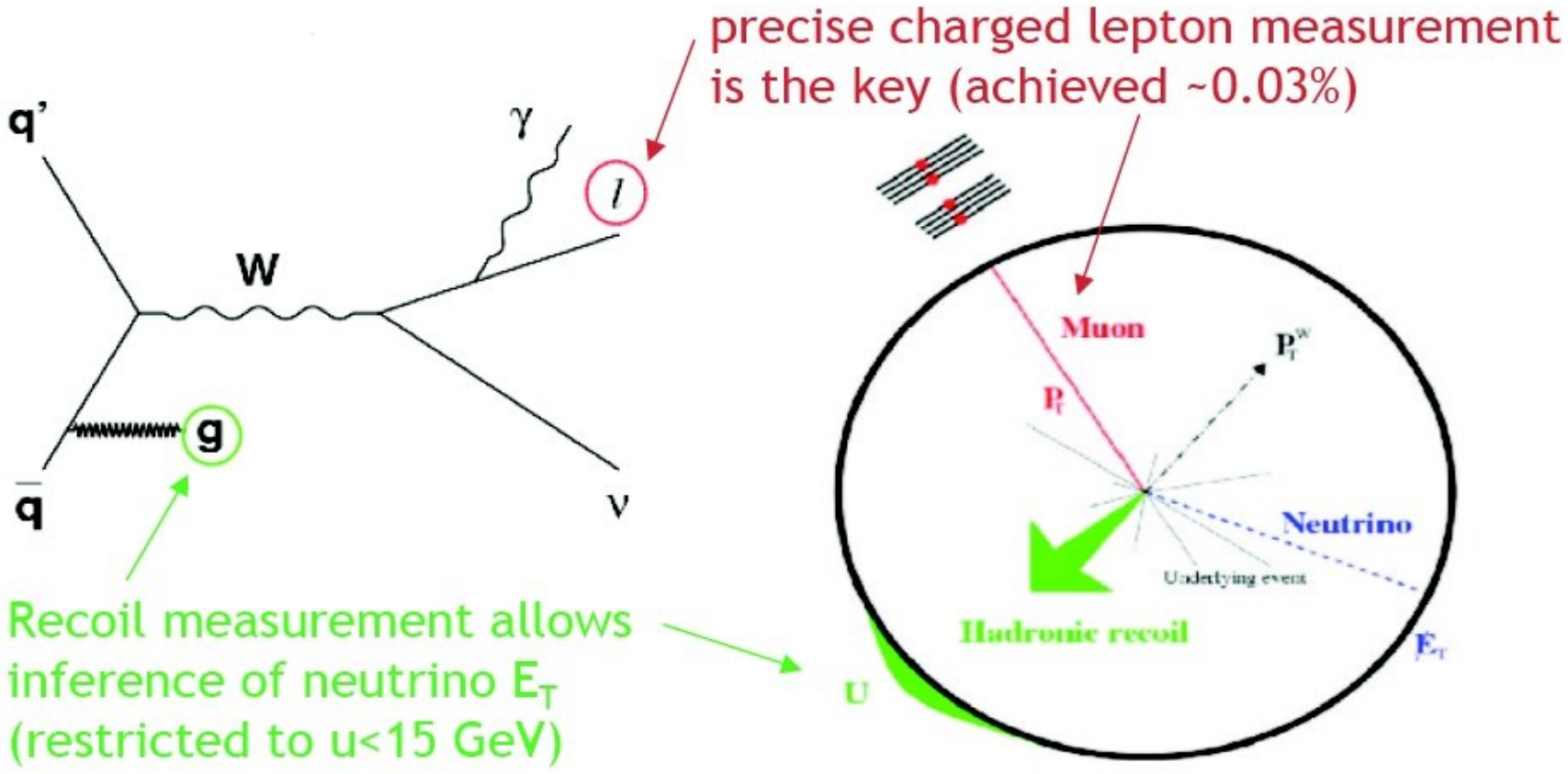
- Radiative corrections are dominated by the top quark and Higgs Boson

$$(m_W - 80.380) = 0.526\left[\left(\frac{m_t}{174}\right)^2 - 1\right] - 0.054\ln\left[\frac{m_H}{100}\right] + f(\Delta\alpha_{EM}, \Delta\alpha_s, m_Z, \ldots)$$

- $\delta m_t \approx 1.8$ GeV
  $\Rightarrow$ 11 MeV shift to m_W
- $\delta(\alpha_{EM}, \alpha_s, m_Z)$
  $\Rightarrow \approx$ few MeV (each) on m_W
- W mass uncertainty currently dominates this relationship
- $\delta m_W = 11$ MeV
  $\Rightarrow$ 19 GeV on 100 GeV Higgs

Experiment	m_W (MeV)
ALEPH	80440 ± 51
DELPHI	80336 ± 67
L3	80270 ± 55
OPAL	80416 ± 53
CDF-I	80433 ± 79
D0-I	80483 ± 84
LEP Average	80376 ± 33
Tevatron-I Average	80454 ± 59
2006 World Average	80392 ± 29

W Production at a Hadron Collider



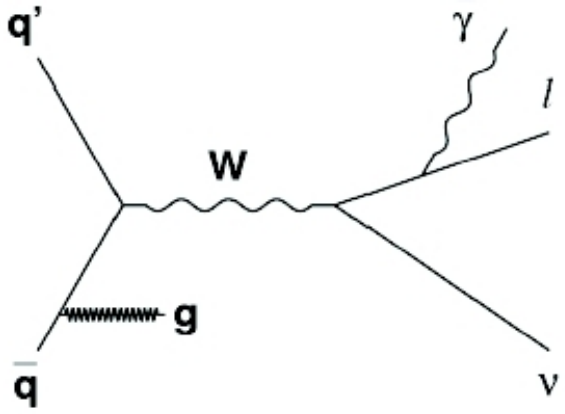
- Combine kinematics to form the *transverse* mass:

$$m_T = \sqrt{2\, p_T(l)\, p_T(\nu)\, \{1 - \cos[\phi(l) - \phi(\nu)]\}}$$

$$m_T = \sqrt{2\, p_T(l)\, |\vec{p}_T(l) + \vec{u}_T|\, \{1 - \cos[\phi(l) - \phi(\nu)]\}}$$

  - Sensitive to underlying event $\equiv |\vec{u}|$ to first order

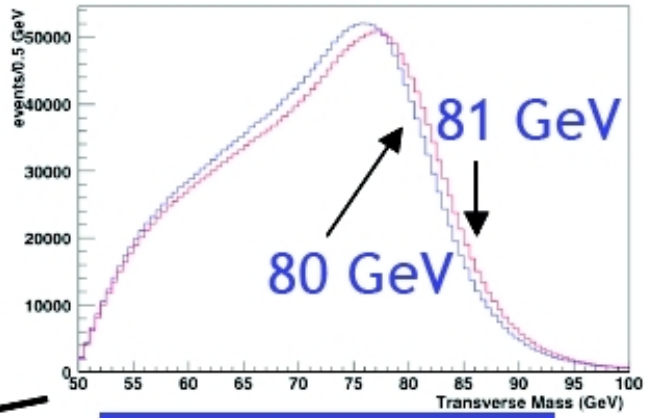
W Mass Strategy



Fast Simulation

- NLO event generator
- Model detector effects

W Mass templates



Detector Calibration

- Tracking momentum scale
- Calorimeter energy scale
- Recoil

Data

+ Backgrounds

Binned likelihood fit

W Mass

Vector Boson Event Selection

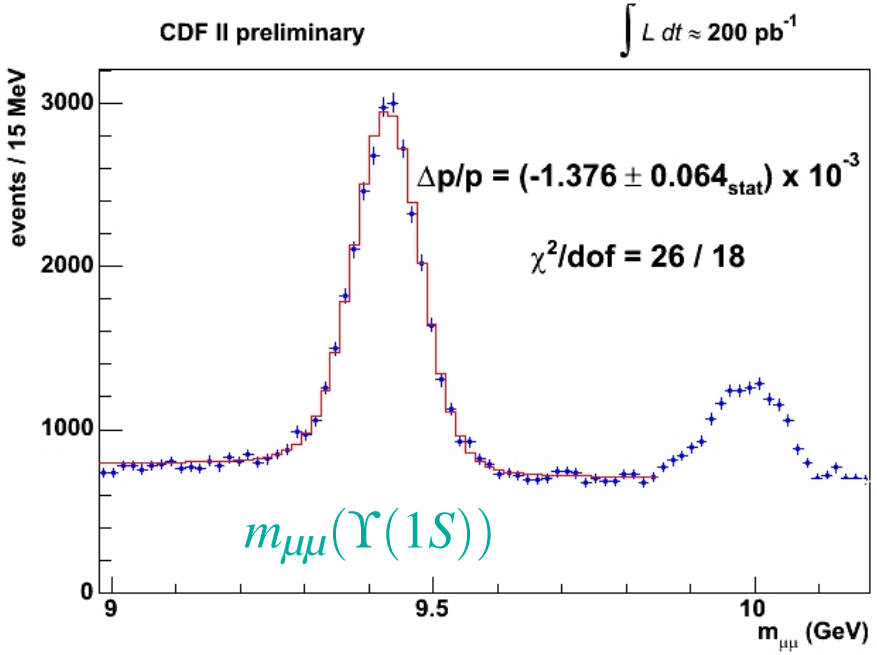
- Select clean W and Z samples
  - Minimize kinematic bias
- Inclusive charged lepton triggers ($p_t >$ 18 GeV)
- Final analysis requires:
  - $E_T(e) >$ 30 GeV or $p_T(\mu) >$ 30 GeV
- W boson selection requires:
  - $\vec{u} <$ 15 GeV and $\not\!\!E_T >$ 30 GeV
- Z boson selection requires two charged leptons

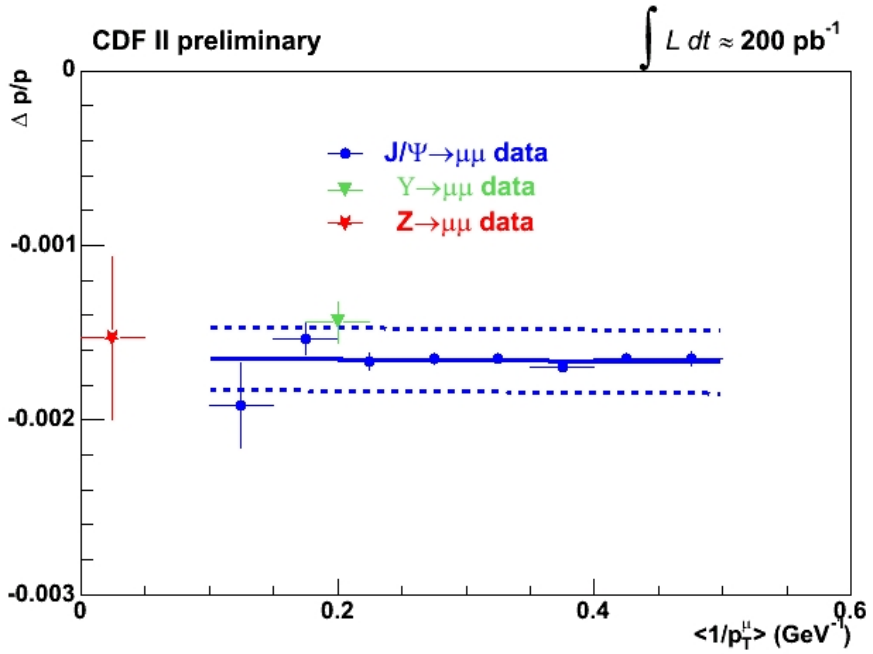
Sample	Candidates
$W \to e\nu$	63964
$W \to \mu\nu$	51128
$Z \to e^+e^-$	2919
$Z \to \mu^+\mu^-$	4960

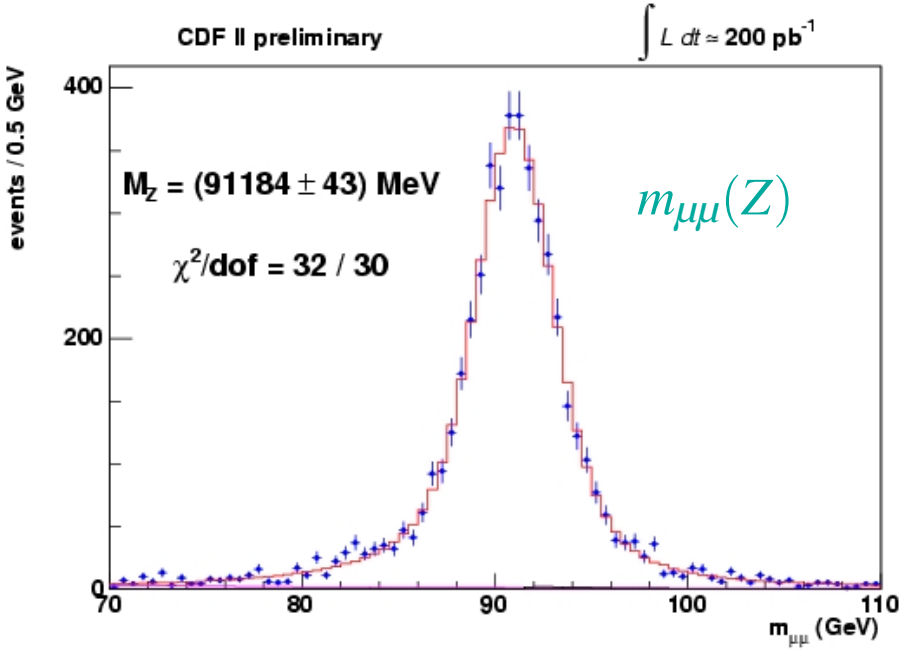
- 200 pb^{-1} sample
- 1/12 $^{\text{th}}$ of data on tape
- Current result includes more W bosons than all four LEP experiments *combined*

Tracker Calibration

- Momentum scale calibration
- Largest systematic for muons
- Constrain/Calibrate with
  - $J/\psi \to \mu^+\mu^-$
  - $\Upsilon(1S) \to \mu^+\mu^-$
- Cross-check with $Z \to \mu^+\mu^-$





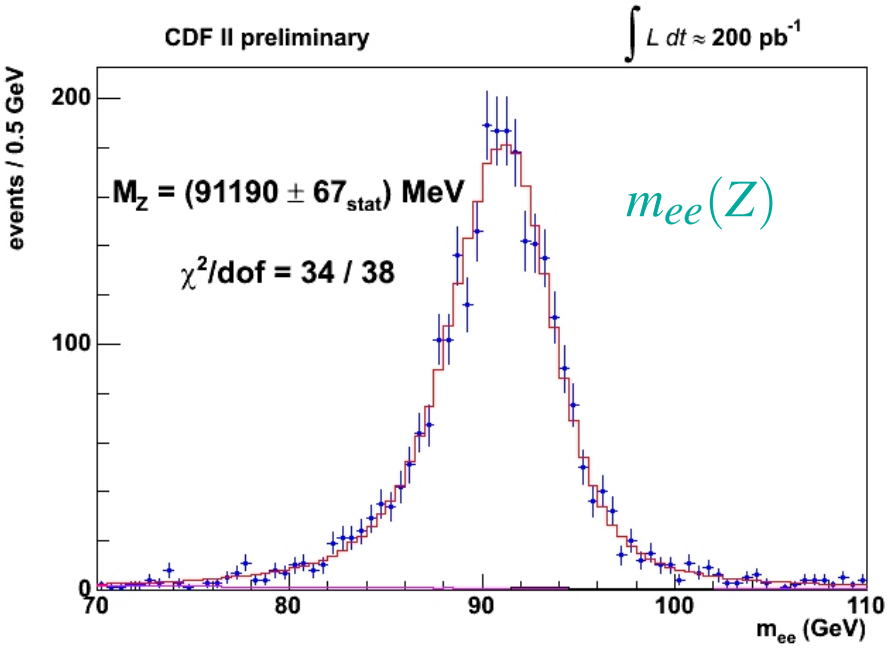


$\Delta m_W = 17$ MeV

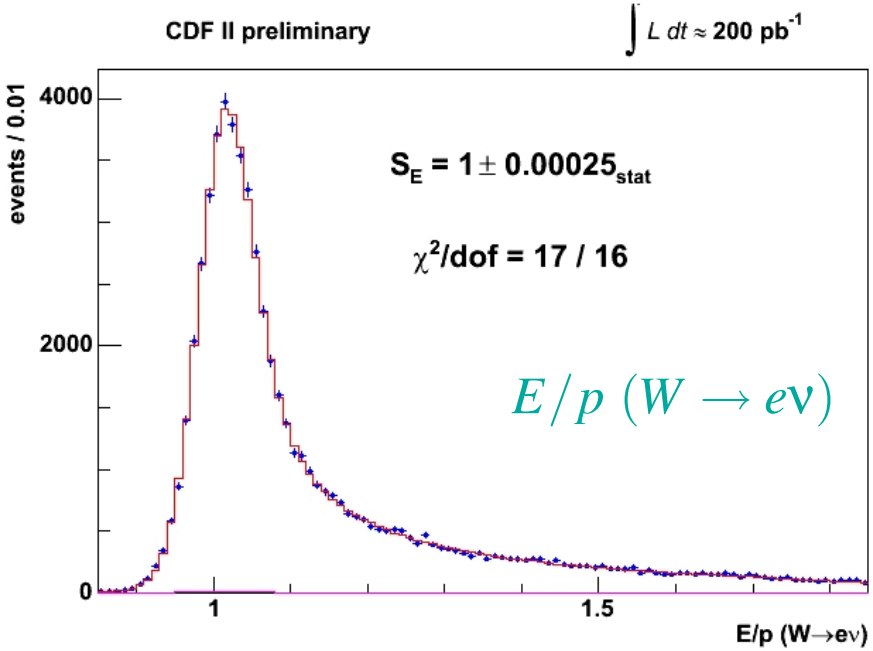
EM Calorimeter Calibration

$$m_Z^{\mathrm{PDG}} = 91188 \pm 2 \text{ MeV}$$

- In-situ EM calorimeter calibration
- Using $W \to e\nu$ electrons
- Material tuned to 2.5 parts in 10^4
- Also EM linearity at a similar level



$\Delta m_W = 30$ MeV

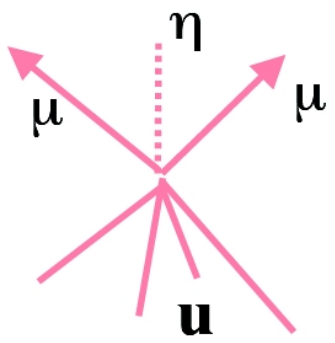


- More than $\sqrt{N}$ improvement since previous measurement

- Tune/constrain calorimeter resolution on Z and E/p $\Rightarrow \Delta m_W = 9$ MeV

Hadronic Recoil Calibration

- Balance hadronic recoil against $Z \to l^+ l^-$

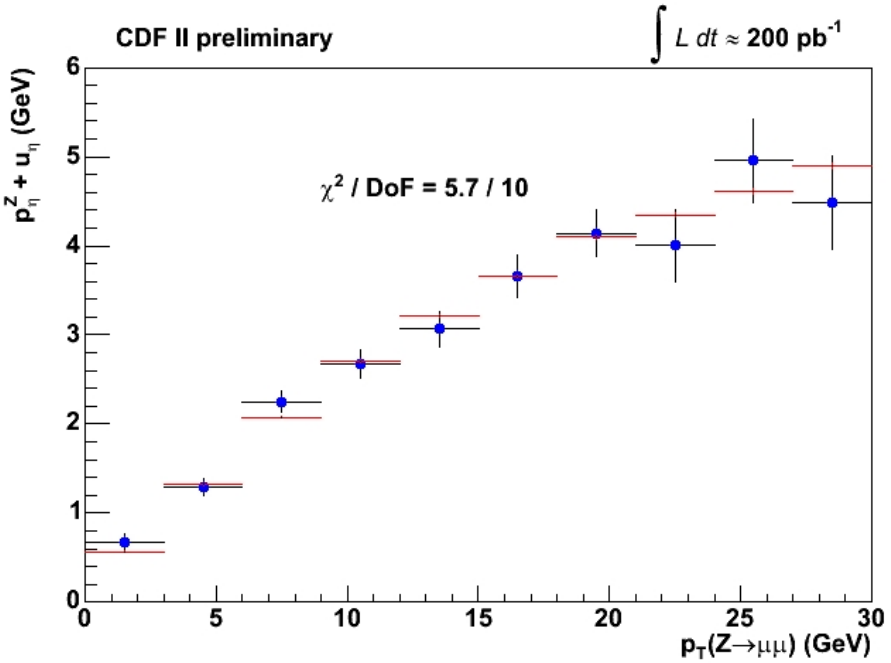


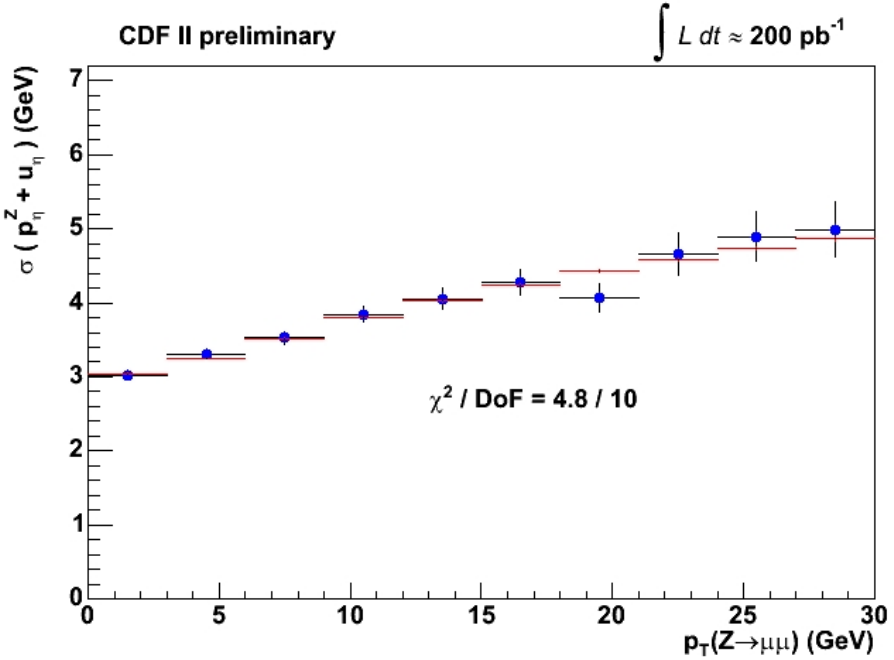
- Calibrate scale along η-axis

$$\Delta m_W = 9 \text{ MeV}$$

- Tune resolution on both projections
  - Low u – underlying event(s)
  - High u – jet-like behaviour

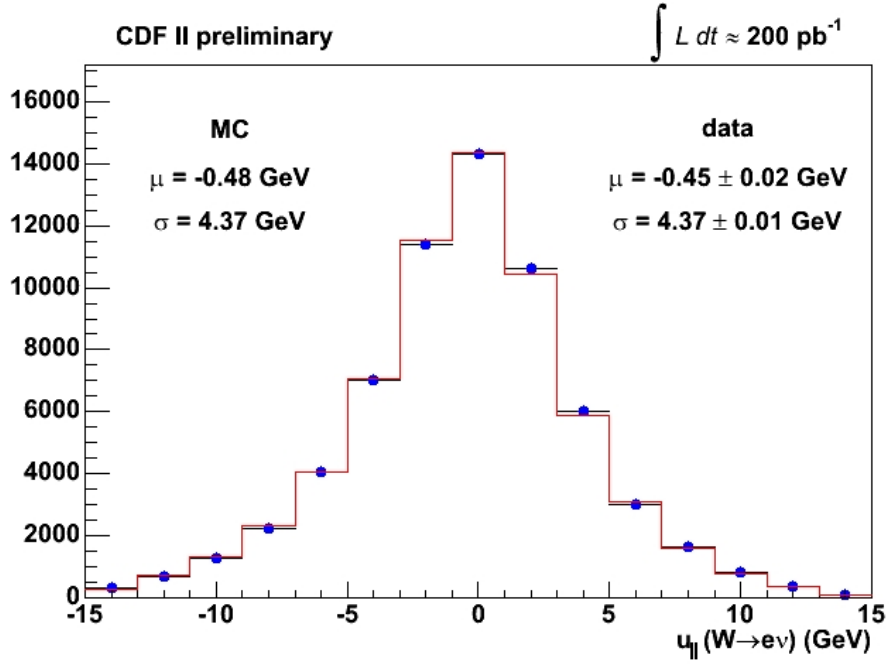
$$\Delta m_W = 7 \text{ MeV}$$

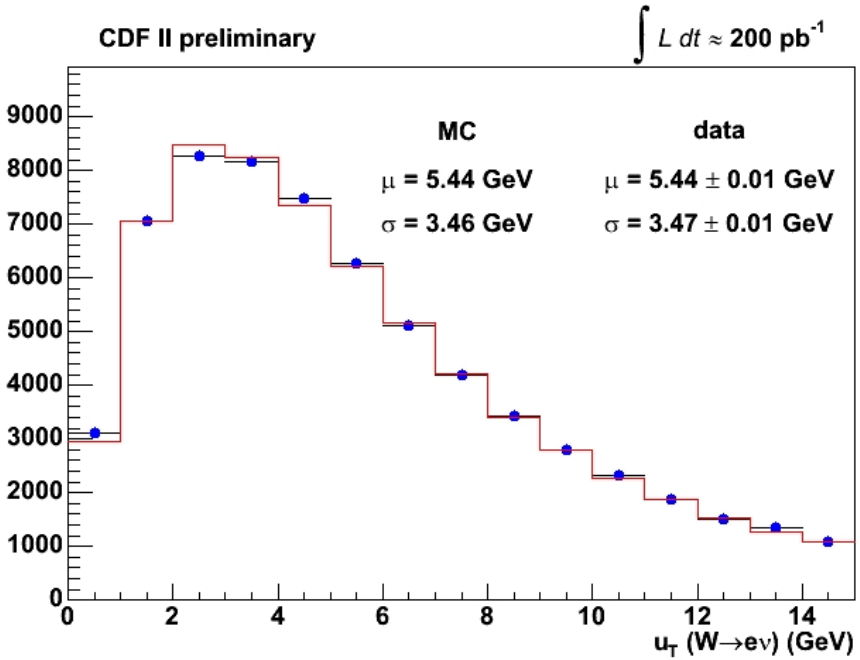




Recoil Model Checks

- Apply the model to $W \rightarrow l\nu$
- Recoil projection along charged lepton: $u_{||}$
  - Directly affects m_T
  - Sensitive to lepton removal, recoil scale and resolution and W decay kinematics

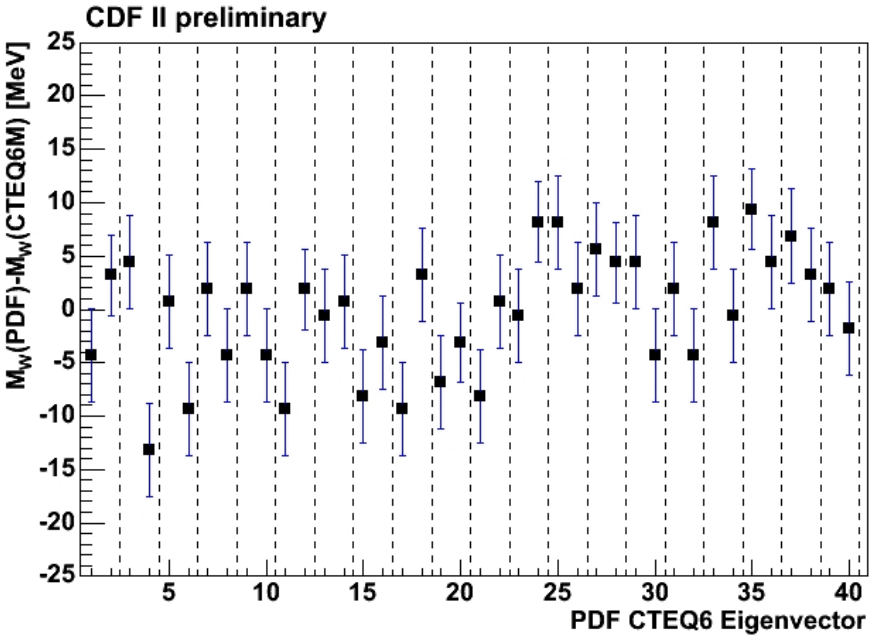




- Recoil distribution sensitive to recoil scale, resolution and input W boson p_T distribution
- Sensitive to non-trivial kinematics

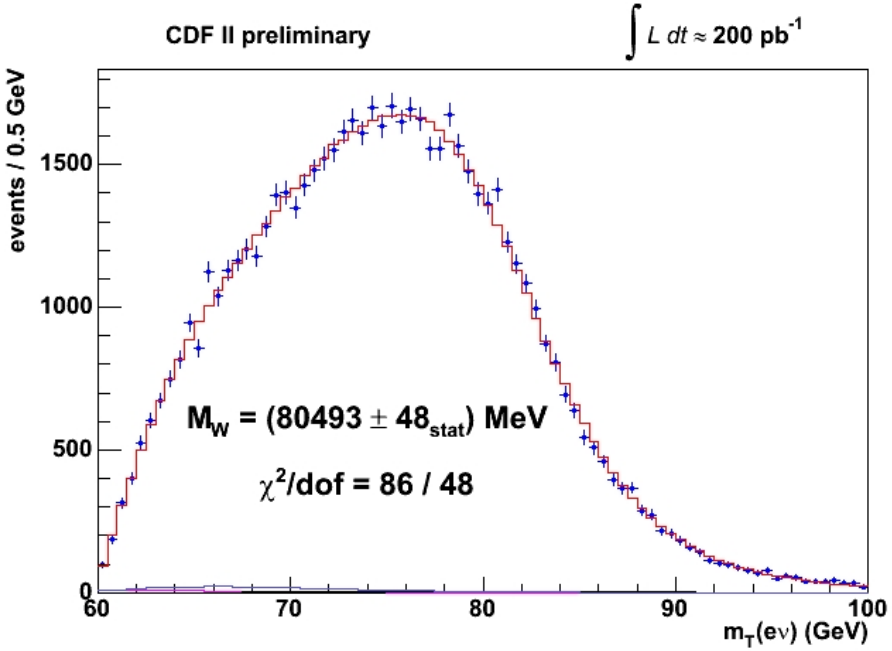
W Boson Production

- Transverse mass shape sculpted by longitudinal momentum
- Dominated by parton distribution functions
  - CTEQ provides Error PDFs
  - 90 % coverage of input data
- $\Delta m_W = 11$ MeV

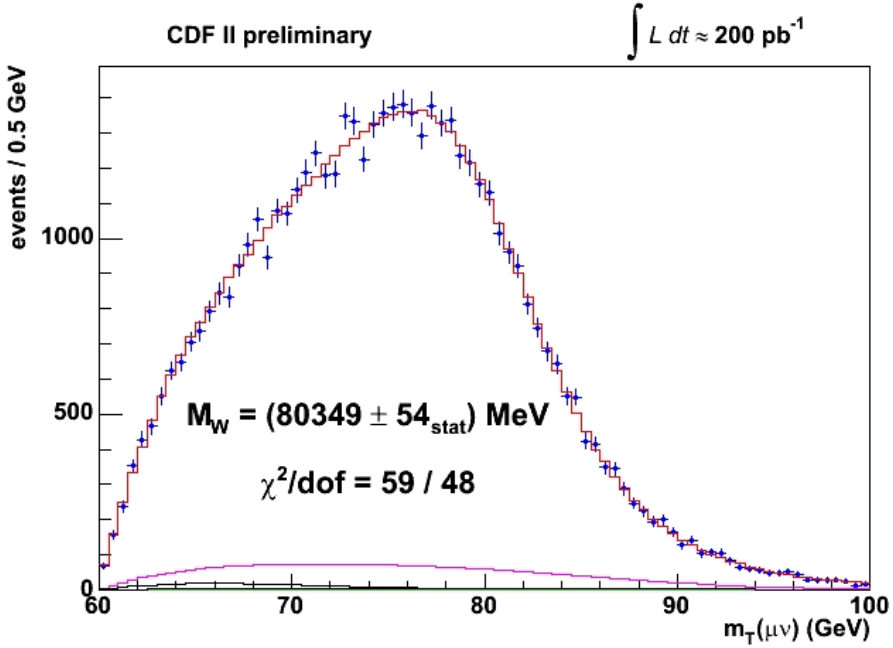


- Lineshape prediction requires model of
  - Gluon radiation (RESBOS, NLO QCD) $\Delta m_W = 3$ MeV
  - Photon radiation (int and ext) (WGRAD, NLO QED) $\Delta m_W = 12$ MeV

W Transverse Mass Fits



Electron m_T



Muon m_T

- Combined they give a result of

$$m_W = 80417 \pm 34(stat) \pm 34(sys) \text{ MeV}$$

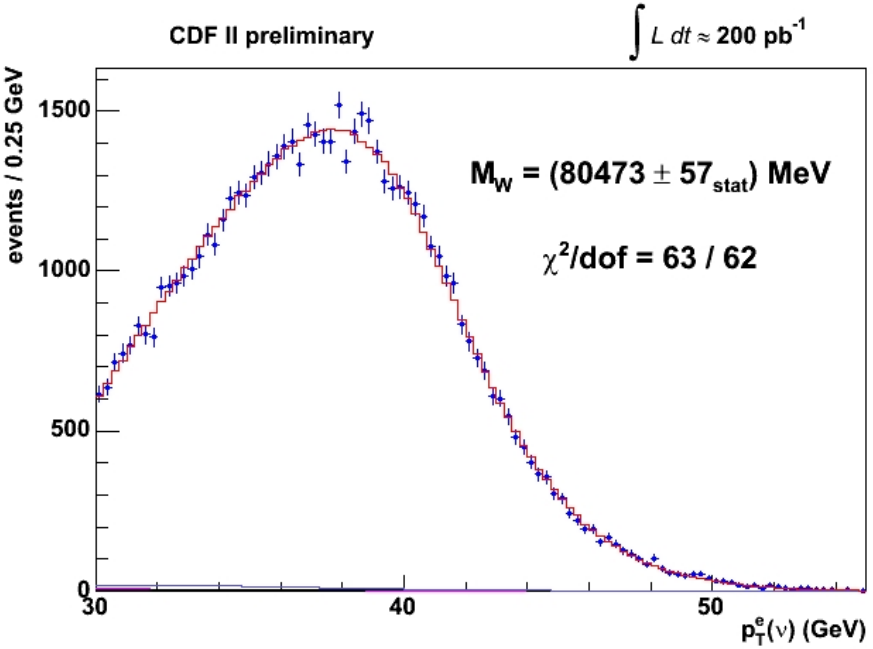
$$P(\chi^2) = 7\%$$

W Transverse Mass Uncertainties

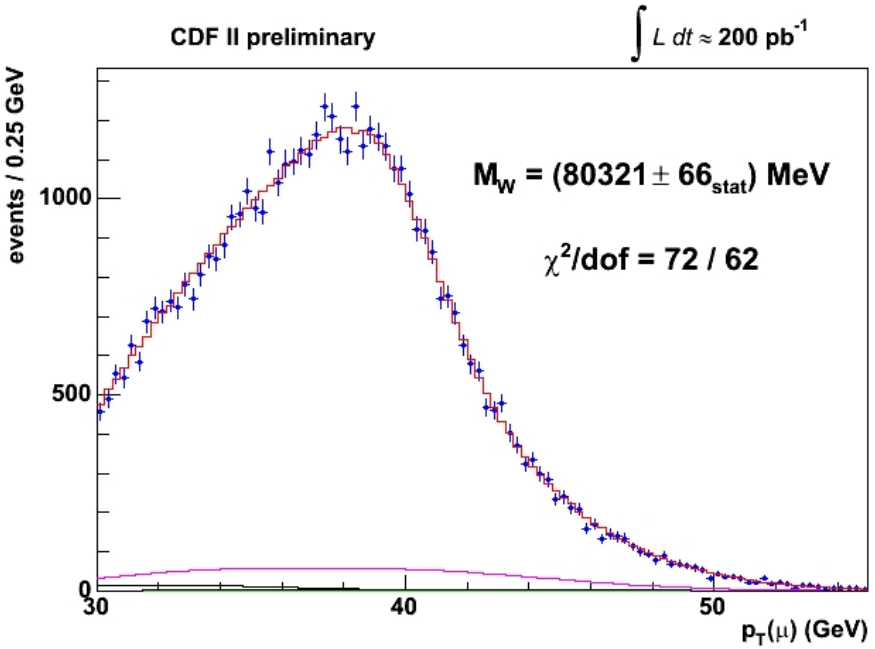
m_T Systematic (MeV)	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
Lepton Removal	8	5	5
Backgrounds	9	9	0
$p_T(W)$ model	3	3	3
Parton Distributions	11	11	11
QED radiation	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total Uncertainty	62	60	26

- Combined electron and muon uncertainty of 48 MeV

Other W Mass Fits



Electron Neutrino p_T



Muon p_T

- Combination of all six fits gives a result of

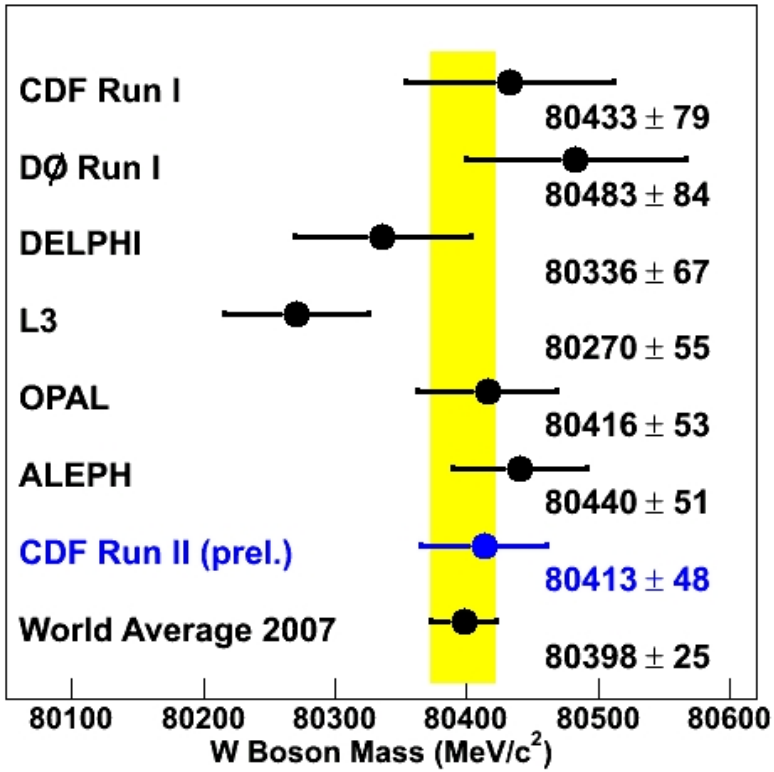
$$m_W = 80413 \pm 48(stat + sys)\ \text{MeV}$$

$$P(\chi^2) = 44\%$$

First Mass Result from Tevatron-II

- Blinded by 100 MeV random offset until analysis finalised
- Different fits of same lepton flavours highly correlated

Fit (MeV)	Result	χ^2/DoF
Electron m_T	80493 ± 48	86/48
Electron p_T	80451 ± 58	63/62
Electron $\not\!\!E_T$	80473 ± 57	63/62
Muon m_T	80349 ± 54	59/48
Muon p_T	80321 ± 66	72/62
Muon $\not\!\!E_T$	80396 ± 66	44/62

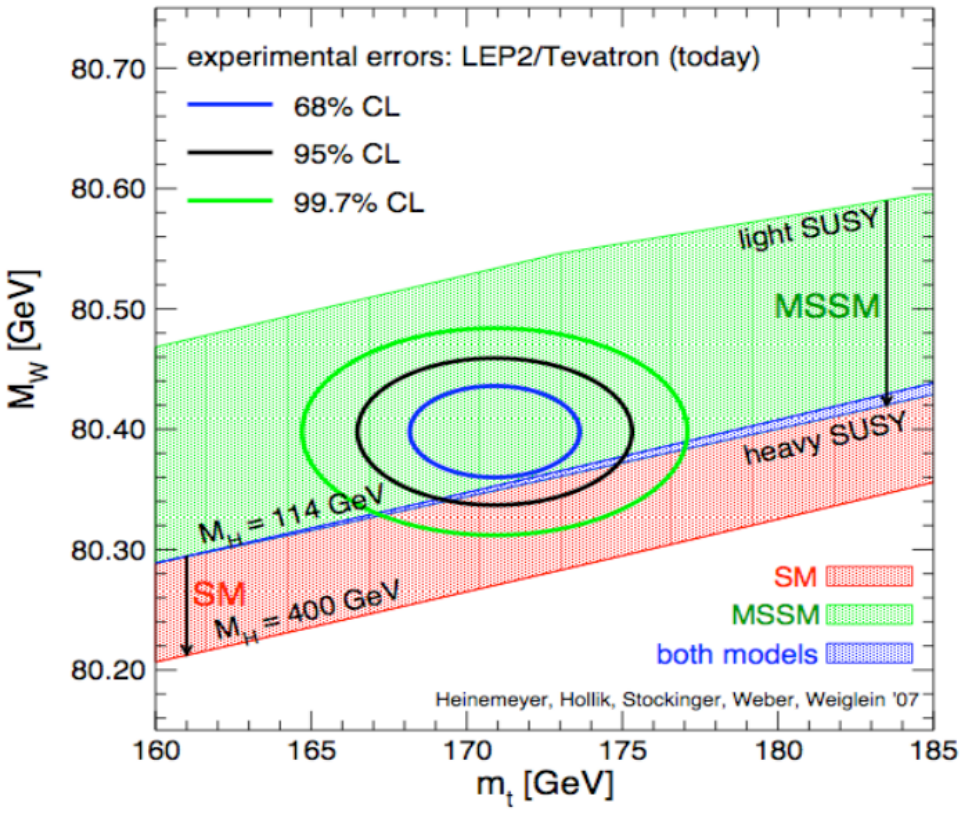


- Combine results from six fits
- Account for both statistical and systematic correlations

- Best single-experiment measurement
- Publication(s) ready for submission

Implications for the Standard Model

- Current state of m_t, m_W, m_H plane



- m_W up from 80392 to 80398 MeV
- Uncertainty from 29 to 25 MeV
- SM prediction for Higgs from:

$$85^{+39}_{-28}\ \text{GeV} \Rightarrow 76^{+33}_{-24}\ \text{GeV}\ \ \text{LEPEWG}$$

- The 95%CL upper limit on m_H drops from 199 to 182 GeV
  - Includes direct search lower bound and recent top mass

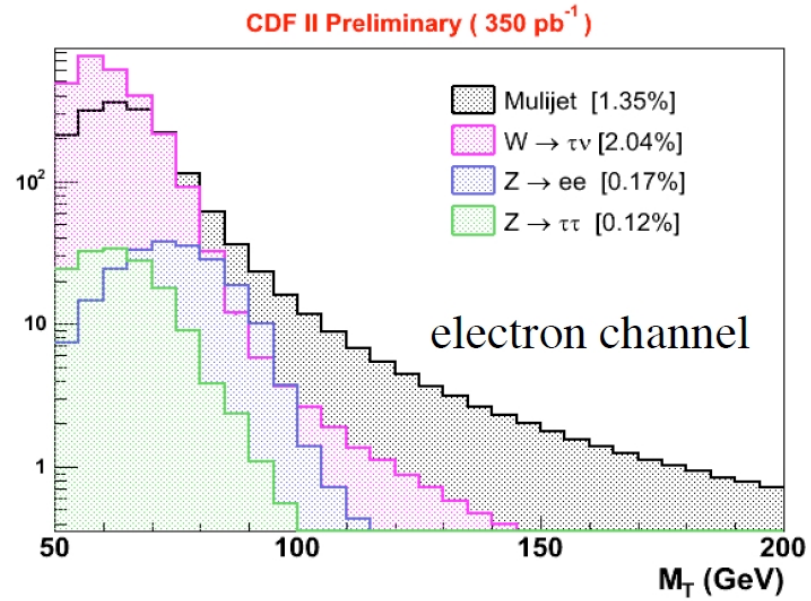
W Width Measurement

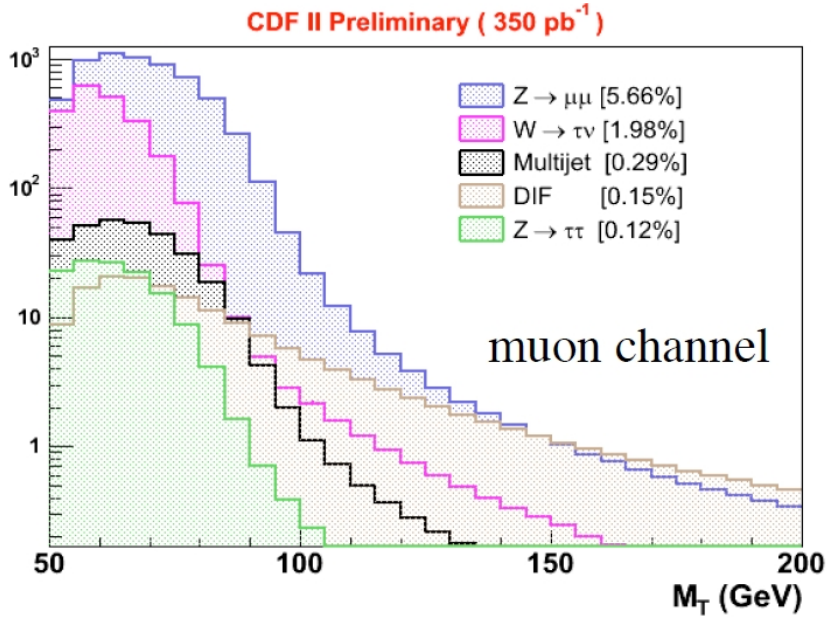
- W width tests Electroweak SM
  - W mass sensitive to Γ_W

$$\Delta m_W \approx \Delta\Gamma_W / 7$$

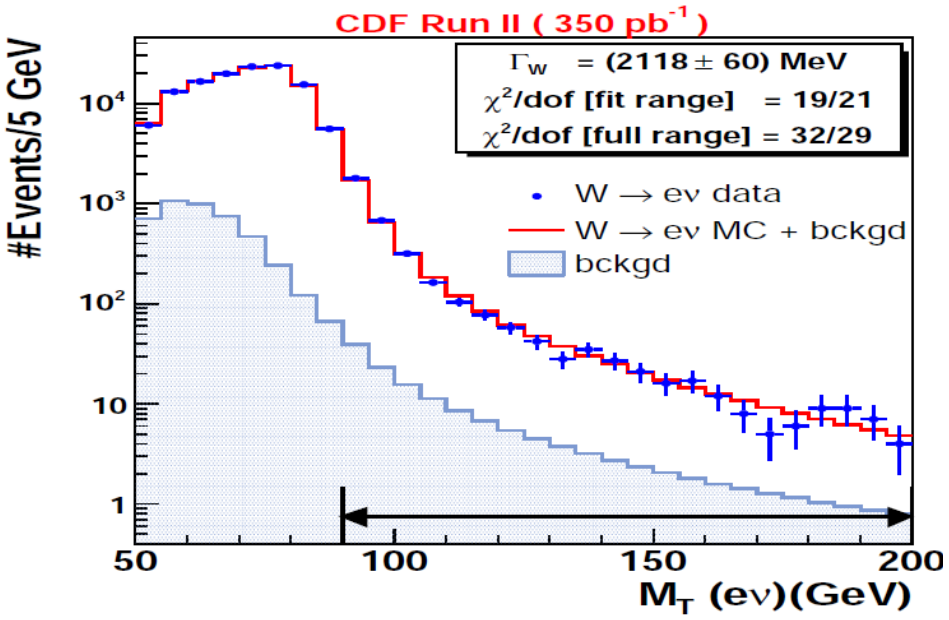
- Γ_W from same dataset(s) as m_W
- Focus on high m_T region
  - Most sensitive to Γ_W
  - Important systematics include
    - Charged lepton resolution
    - Backgrounds
    - W recoil model
- Use 350 pb^{-1}

Γ_W Backgrounds

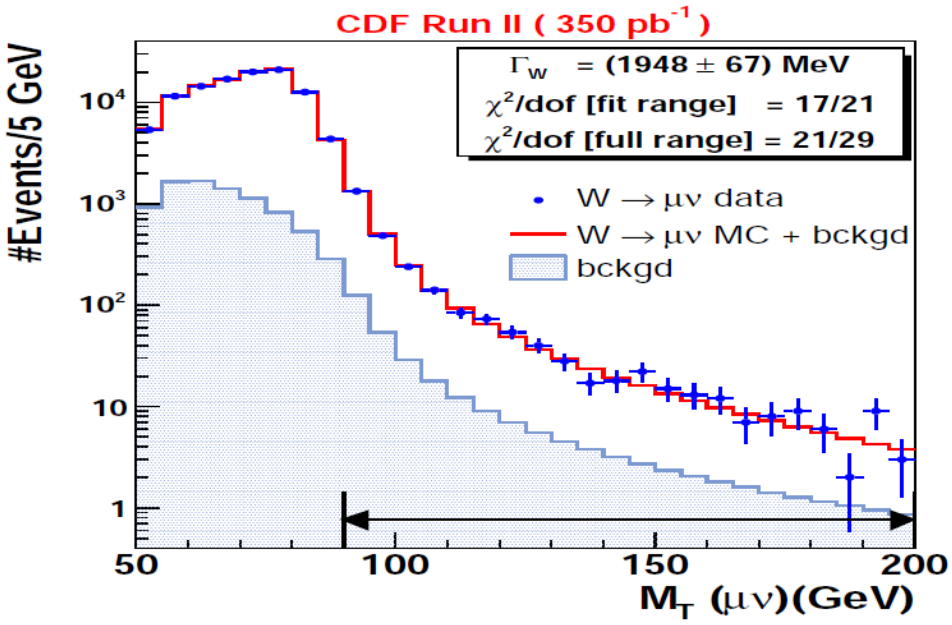




Fits for W Width



Electron m_T



Muon m_T

- Combined they give a result of

$$\Gamma_W = 2032 \pm 71 (stat + sys) \text{ MeV}$$

$$P(\chi^2) = 20\%$$

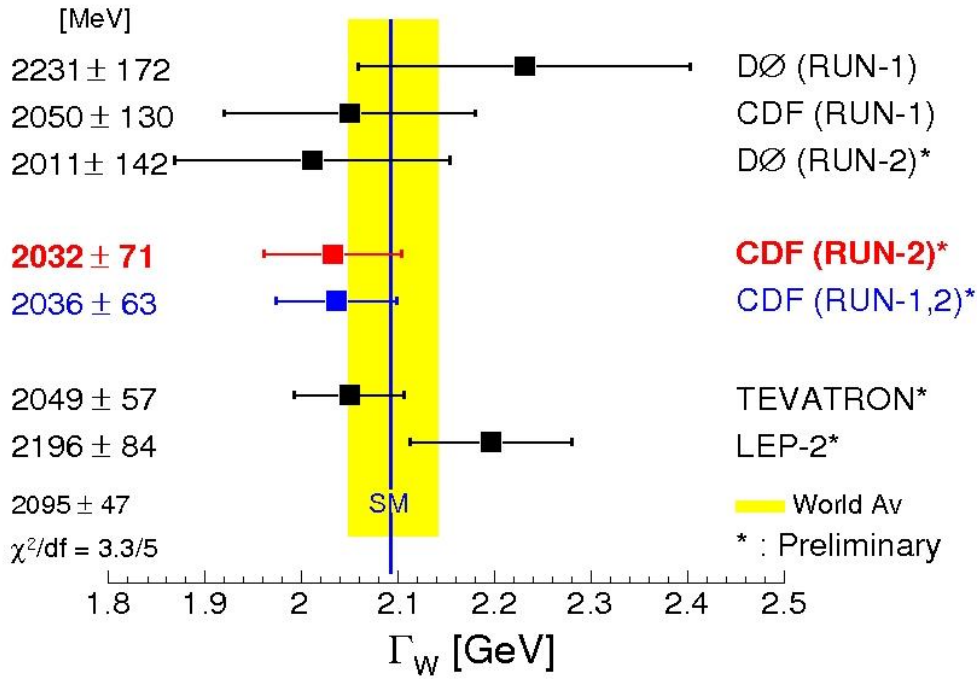
W Width Results

- Study similar systematics
- Constrain from control samples

Γ_W Uncertainty (MeV)	e	μ	Common
Lepton Scale	21	17	12
Lepton Resolution	31	26	0
Simulation	13	0	0
Recoil	54	49	0
Lepton ID	10	7	0
Backgrounds	32	33	0
$p_T(W)$ model	7	7	7
Parton Distributions	16	17	16
QED radiation	8	1	1
Total Systematic	78	70	23
Statistical	60	67	0
Total Uncertainty	98	97	23

  - Combine channels
    - Account for correlations

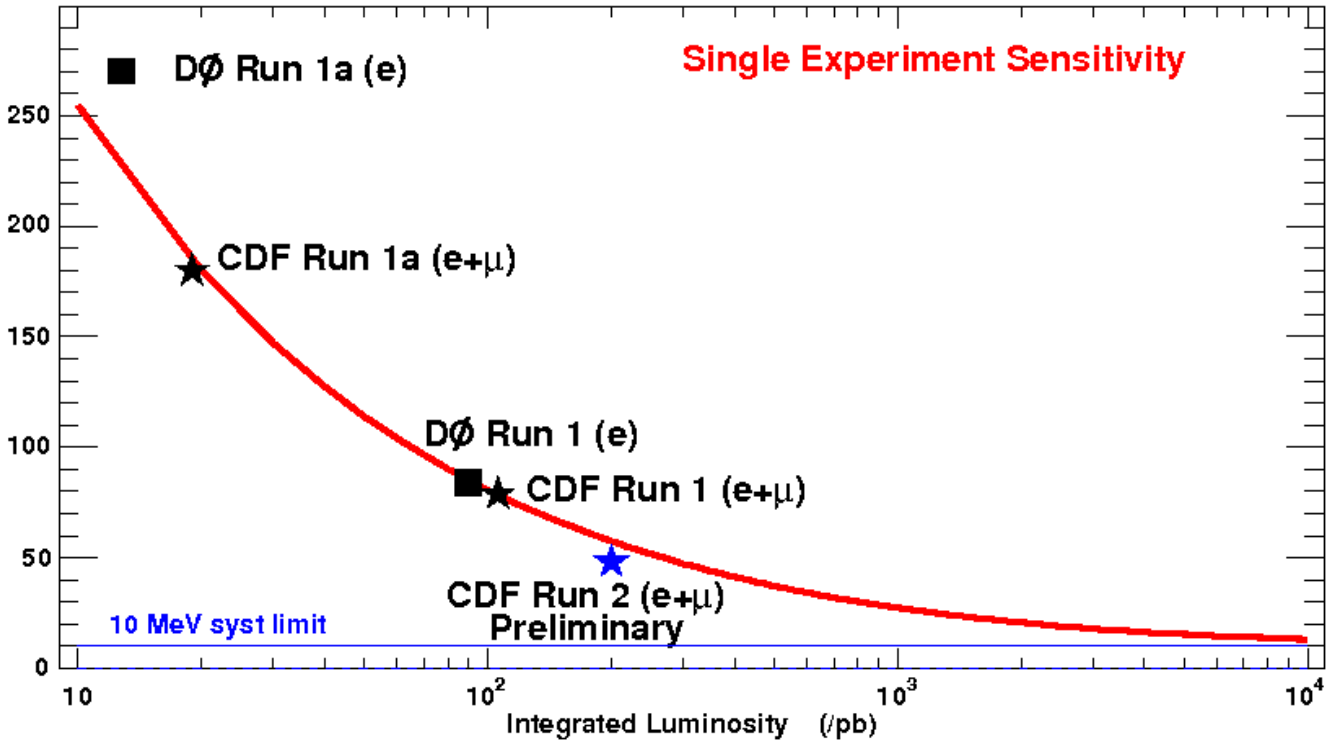
- SM prediction $\delta\Gamma_W \approx 2$ MeV



- Pushing to a new level of precision
- Publication in preparation

W Mass Prospects at CDF

- Only analysed 1/12th of data currently on tape
- Before this result we were projecting 20-30 MeV W mass syst. limit



- Beginning analysis of full dataset
- $\Rightarrow$ W mass uncertainty of 25 MeV (stat+sys) possible
- Ultimately CDF should get to a 15-20 MeV overall uncertainty

Longer Term Outlook

- Beyond $\approx$ 25 MeV mass measurement(s?) at Tevatron
- ATLAS beginning to study O(10 MeV) production systematics
- Should expect sub-10 MeV mass measurement(s) from LHC
- ILC will presumably do even better
- Hopefully cross-checking Standard Model prediction
  - Having observed Higgs, or analog, and measured mass
- $\delta\Gamma_W \approx$ 20 MeV feasible at Tevatron

Contribution	δm_W
$\delta m_H = 10$ GeV	-5.5
$\delta m_t = 1$ GeV	+6.1
$\delta m_Z = 2.1$ MeV	+2.6
$\delta \alpha_{EM} = 0.00036$	-6.5
$\delta \alpha_s = 0.0027$	-1.7

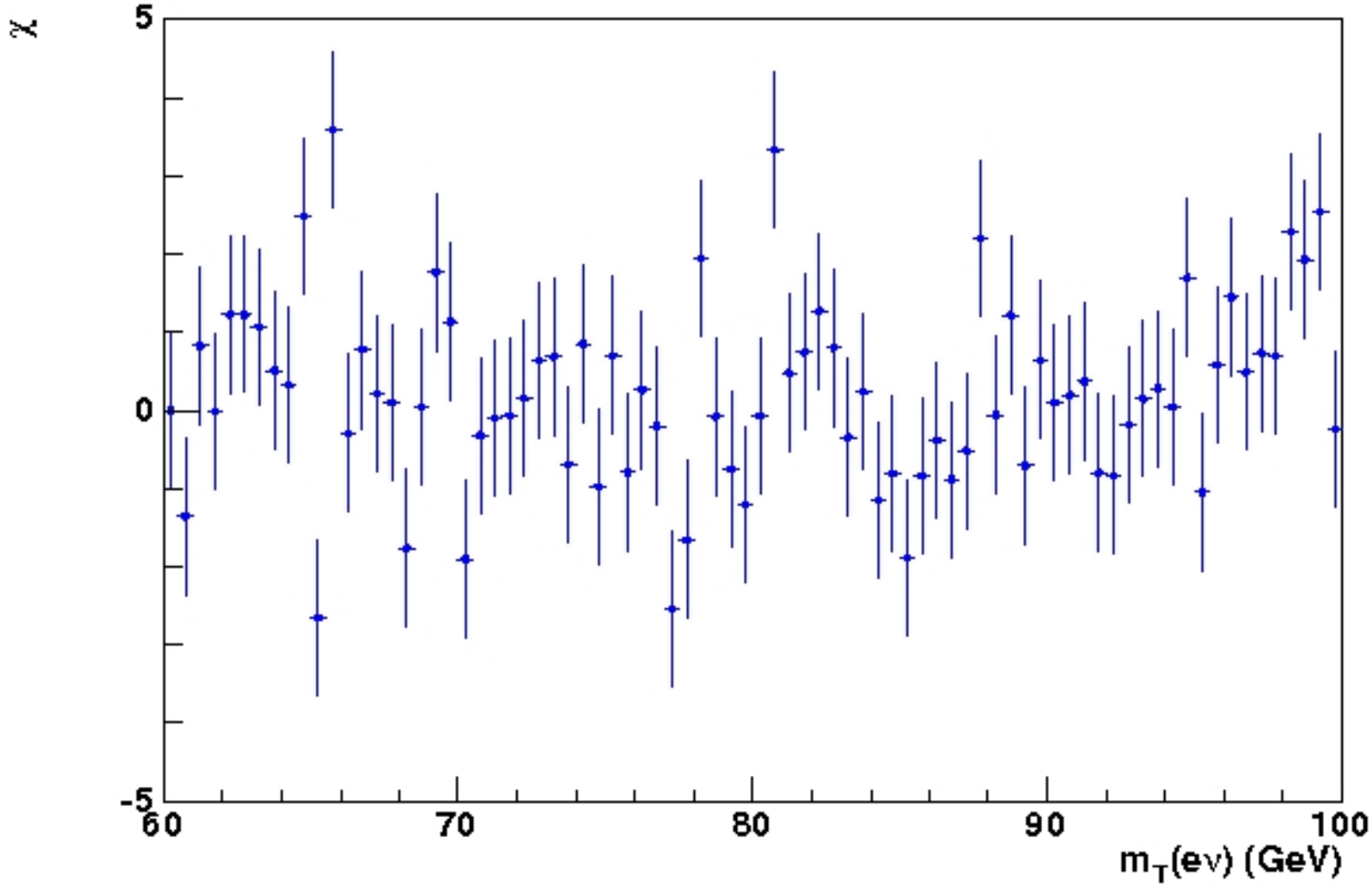
Awramik *et al.* PRD69, 053006

Charged Lepton Fit Uncertainties

p_T (MeV)	Electrons	Muons	Comm
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	17	17	17
Recoil Resolution	3	3	3
Lepton Removal	0	0	0
Backgrounds	9	19	0
$p_T(W)$ model	9	9	9
Parton Distributions	20	20	20
QED radiation	13	13	13
Total Systematic	45	40	35
Statistical	58	66	0
Total Uncertainty	73	77	35

Neutrino Fit Uncertainties

$\not{E}_T$ (MeV)	Electrons	Muons	Comm
Lepton Scale	30	17	17
Lepton Resolution	9	5	0
Recoil Scale	15	15	15
Recoil Resolution	30	30	30
Lepton Removal	16	10	10
Backgrounds	7	11	0
$p_T(W)$ model	5	5	5
Parton Distributions	13	13	13
QED radiation	9	10	9
Total Systematic	54	46	42
Statistical	57	66	0
Total Uncertainty	79	80	42


χ
5
0
-5
60
70
80
90
100
m_T(eν) (GeV)